Detection of water at z=0.685 towards B0218+357

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ABSTRACT

We report the detection of the H_2O molecule in absorption at a redshift z=0.68466 in front of the gravitationally lensed quasar B0218+357. We detect the fundamental transition of ortho–water at 556.93 GHz (redshifted to 330.59 GHz). The line is highly optically thick and relatively wide (15 km/s FWHM), with a profile that is similar to that of the previously detected CO(2–1) and HCO^+(2–1) optically thick absorption lines toward this quasar. From the measured level of the continuum at 330.59 GHz, which corresponds to the level expected from the power–law spectrum $S(\nu) \propto \nu^{-0.25}$ already observed at lower frequencies, we deduce that the filling factor of the H_2O absorption is large. It was already known from the high optical thickness of the CO, ^{13}CO and C^{18}O lines that the molecular clouds entirely cover one of the two lensed images of the quasar (all its continuum is absorbed); our present results indicate that the H_2O clouds are covering a comparable surface. The H_2O molecules are therefore not confined to small cores with a tiny filling factor, but are extended over parsec scales. The H_2O line has a very large optical depth, and only isotopic lines could give us the water abundance. We have also searched for the 183 GHz line in absorption, obtaining only an upper limit; this yields constraints on the excitation temperature.

Subject headings: BL Lacertae objects: individual (B0218+357) — galaxies : abundances — galaxies : ISM — ISM : molecules — quasars : absorption lines — radio lines : ISM

1. Introduction

Water is believed to be one of the most abundant molecules in the interstellar medium (ISM). It can be formed through gas–phase chemistry in cold, dense and thick clouds, with an abundance ratio H_2O/H_2 between 10^{-7} and 10^{-5}, depending on the chemical models, the reactions rates used, the C/O abundance in the gas phase (Leung, Herbst & Huebner 1984; Langer & Graedel 1989); in non–dissociative shocks the abundance ratio is calculated to be as high as 10^{-4} (Draine, Roberge & Dalgarno 1983; Kaufman & Neufeld 1996). The H_2O abundance can also be enhanced through evaporation of grain mantles in star–forming hot cores (Jacq et al. 1988; Brown, Charnley & Millar 1988; Gensheimer, Mauersberger & Wilson 1996), so H_2O could play a major role in the cooling of molecular clouds, and in the oxygen budget of the ISM. Unfortunately, the broad atmospheric water lines prevent a direct detection from the ground in our own Galaxy; up to now, no thermal emission from the main isotopomer in its fundamental lines has been detected, and the H_2O abundance in the ISM remains poorly known. Attempts have been made to determine the H_2O abundance through observations of the isotopomers HDO and $H_2^{18}O$ (Henkel et al. 1987; Jacq et al. 1988, 1990; Wannier et al. 1991; Gensheimer et al. 1996), and through observations of the precursor ion H_3O^+ (Phillips, van Dishoeck & Keene 1992). Abundances of the normal isotopomer of H_2O around 10^{-5} have been deduced. This is also confirmed by the detection in Orion of absorption lines at 2.66 microns with the Kuiper Airborne Observatory (KAO) (Knacke & Larson 1991). The latter authors found an ortho–para ratio of 1, which confirms that water had no time, after sublimation from grains, to reach the equilibrium high temperature ratio of 3. Also the deuterated substitute HDO reveals a high degree of fractionation (HDO/H_2O = 100 D/H), which implies H_2O formation at low temperatures.

Since some of the H_2O submillimeter and FIR transitions are population inverted,

causing maser emission with a very high flux, they can be detected from the ground even at 183 GHz (Cernicharo et al. 1994). Another method to avoid atmospheric absorption lines is to observe a remote object, for which the lines are redshifted outside the broad atmospheric counterpart. Only one tentative detection has been reported so far: the 752 GHz para–water line in the $z = 2.28$ galaxy IRAS 10214+47 (Encrenaz et al. 1993; Casoli et al. 1994). The emission in this remote starburst galaxy is apparently significantly enhanced by gravitational lensing. Very recently, observations with the ISO satellite of the $2_{12} - 1_{10}$ 179.5 μm line of ortho–water in absorption against the continuum of the galactic center (SgrB2, Cernicharo et al. 1997) have revealed that the H_2O molecule is abundant over very extended regions. It has also been detected in absorption in front of massive young stars with strong IR continuum, around 6μm within the bending vibration series (Helmich et al. 1996; van Dishoeck & Helmich 1996). Abundances of a few 10^{-5} are deduced, with a tendency of scaling with the amount of warm gas. Even higher abundances ($(3-8) \times 10^{-4}$) have been derived from H_2O emission from the stellar wind of W Hya with ISO–SWS and LWS, but the exact figures depend on the outflow modelisation (Barlow et al. 1996; Neufeld et al. 1996).

Here we report the first detection in absorption at high redshift of an H_2O line. The high redshift allows us to avoid the high opacity of the terrestrial atmosphere near the rest frequency, and because absorption is against a small continuum source, excellent spatial resolution is achieved, equal to the angular size of the B0218+357 quasar core, which is only of the order of 1 milli-arcsec (Patnaik, Porcas & Browne 1995). At the distance of the absorber ($z = 0.68466$, giving an angular distance of 1089 Mpc, for H_0=75 km s^{-1} Mpc^{-1} and q_0 =0.5), this corresponds to only 5 pc.

2. Observations

The observations were made with the IRAM 30m telescope at Pico Veleta near Granada in Spain in March 1997. Table 1 displays the observational parameters. Several SIS receivers were used simultaneously: at 3mm, the receiver was tuned to the H_2O 3_{13}-2_{20} para line at 183 GHz, redhifted to 108.811 GHz to obtain an estimate of the excitation temperature (the lower level of this transition corresponds to a temperature of 190 K). The single–sideband (SSB) system temperature was 180 K and the rejection level of the image sideband $\sim$30 dB. At 0.8mm, the H_2O 1_{10}-1_{01} ortho line at 557 GHz, redshifted to 330.592 GHz, was observed. The receiver was operating in single–sideband, with a rejection level of a factor 4 (6 dB measured on Orion); its SSB receiver temperature was 90 K and the system temperature was between 400 and 2000 K, depending on the atmospheric humidity, with an average of 700 K. Two 512×1 MHz filterbanks and an autocorelator backend were used. Here only the 1 MHz resolution spectra are presented, binned to a velocity resolution of a few km/s.

The observations were done with a nutating subreflector, with a beam–throw of 1' in azimuth and a switching frequency of 0.5 Hz. The temperature scale was calibrated every 10 minutes by a chopper wheel on an ambient temperature load, and on liquid nitrogen. Pointing was checked on broadband continuum sources. The relative pointing offsets between the 2 receivers were of the order of 4". The frequency tunings and rejection levels were checked by observing known molecular lines towards Orion, DR21 and IRC+10216. The integration time was 8 and 20 hours on the 183 GHz and 557 GHz lines respectively, and a noise–level of 1.1 and 1.3 mK in the T_A^* antenna temperature scale was obtained, with a velocity resolution of 9 km s^{-1}. The forward and beam efficiencies at each frequency are displayed in Table 1.

In order to derive the continuum flux, B0218+357 was observed regularly with a

continuum backend and in a fast switching mode (4 times higher than in the line observing mode). The continuum level from line observations obtained under good sky conditions was also used. The two estimates of the continuum flux agree.

The BL Lac object B0218+357 was selected for this first search for H_2O in absorption because it is the absorbing system at high redshift with the highest column density (Wiklind & Combes 1995). The remote quasar ($z_e \approx 0.9$, e.g. Browne et al. 1993) is gravitationally lensed by a foreground galaxy at z=0.68466, which produces the absorption. The radio image of the quasar is composed of two distinct flat–spectrum cores (A and B), with a small Einstein ring surrounding the B image, of 335 milli–arcsecond (mas) in diameter (Patnaik, Browne & King 1993). Since the ring has a steep spectrum, it is best interpreted as the image of a jet component, or a hot spot or knot in a jet that happens to lie in the line of sight to the center of the lens. Owing to its steep spectral index, the Einstein ring gives a negligible contribution to the continuum flux at millimeter wavelengths. The intensity ratio between the two images is A/B $\approx$ 3–4 at several radio wavelengths, but the B–component has varied in flux by $\approx$ 10% in a few months (O'Dea et al. 1992; Patnaik et al. 1993). Since the depth of the molecular absorption is less than the continuum level, but the absorption is optically thick, it follows that the absorbing material does not cover the whole surface of the continuum source. It is likely that only one image of the quasar is covered by molecular clouds, since the two images A and B are separated by 1.8 kpc at the absorber distance. The fraction of the total continuum which is absorbed is $\approx$ 33%.

3. Results and discussion

Figure 1 presents our H_2O detected spectrum, compared to those of HCO^+(2–1) and CO(2–1) previously detected with the IRAM 30m telescope (Wiklind & Combes 1995; Combes & Wiklind 1995). The linewidths are very similar, respectively 15, 16 and 15 km/s

for H_2O, HCO^+(2–1) and CO(2–1), determined by gaussian fits. This is a strong indication that the H_2O line is optically thick, as the ^{13}CO and C^{18}O isotopic lines have been detected, with progressively reduced line–widths (Combes & Wiklind 1995). The 3_{13}-2_{20} para line at 183 GHz was not detected. The 3σ upper limit presented in Table 1 were derived by assuming the same linewidths for the two H_2O lines.

The redshift of the absorbing molecular gas, z= 0.68466 ± 0.00001 (Wiklind & Combes 1995), puts the redshifted $H_2O(1_{10} - 1_{01})$ line at 330.593 GHz, which is close to the frequency of the ^{13}CO(3–2) transition at z=0 of 330.588 GHz (e.g. Lovas 1992). The difference in velocity is only 4.1 km/s. Nevertheless, it is highly unlikely that the absorption line seen at 330.59 GHz is caused by a Galactic ^{13}CO(3–2) transition. First of all, the depth of the absorption as well as the width of the H_2O line is the same as those of the lines of redshifted CO(2–1), ^{13}CO(2–1), C^{18}O(2–1), HCO^+(2–1), HCN(2–1), etc. (Combes & Wiklind 1996) – in itself a strong indication that our new line is from redshifted water. Secondly, a search through all our spectra, covering several GHz, does not reveal any molecular transition at z=0, although several relatively strong lines should be present (for instance: SO($3_4 - 2_3$), SiO(3–2) $v = 0$). Thirdly, B0218+357 is situated at Galactic coordinates $l = 142.6°$, $b = -23.5°$. This means that unless Galactic absorption occurs very locally, Galactic rotation would displace the z=0 line of ^{13}CO(3–2) to negative velocities. If there is local gas, it is likely to be extended on scales of 1' (the throw of our telescope beam) and the observing procedure with a nutating subreflector would effectively cancel Galactic absorption.

Figure 2 displays our continuum measurements, together with a compilation of previous results in the literature for lower frequencies. Within the 1σ error bars, the continuum spectrum can be fitted with a power law of slope -0.25. From our previous detection of the C^{18}O(2–1) line with an optical depth of ≈ 3 (Combes & Wiklind 1995), we deduced an

optical depth of 1500 for the $^{12}CO(2–1)$ line. Since the H_2O abundance is likely to be only 10 times lower than that of CO, while its dipole moment $\mu = 1.8$ debye is 18 times higher, we expect an H_2O optical depth about 30 times higher than CO for cold gas, since τ/N scales as μ^2. This clearly prevents any estimation of the H_2O abundance; however the line strength S is about ten times lower for the 183 Ghz line, so the upper limit on the 183 GHz line provides a constraint on the excitation temperature.

The total column density of the H_2O molecule, observed in absorption between the levels $l \longrightarrow u$ with an optical depth τ at the center of the observed line of width Δv at half–power is:

$$N_{H_2O} = \alpha f(T_x) \frac{\nu^3 \tau \Delta v}{g_u s_I A_u} \ ,$$

where α is a constant ($8\pi/c^3$), ν is the frequency of the transition, g_u the statistical weight of the upper level (= 2 J_u+1), A_u the Einstein coefficient of the transition, T_x the excitation temperature, and

$$f(T_x) = \frac{Q(T_x) exp(E_l/kT_x)}{1 - exp(-h\nu/kT_x)} \ ,$$

where $Q(T_x)$ is the partition function. The factor s_I is the nuclear spin statistical weight, equal to $^3/_4$ for ortho states and $^1/_4$ for para states.

For the sake of simplicity, we adopt the hypothesis of restricted thermodynamical equilibrium conditions, i.e. that the excitation temperature is the same for all the H_2O lines. Also, we assume an ortho/para ratio of 3. Replacing in the above formula the molecular parameters from de Lucia, Helminger & Kirchoff (1974), and assuming the abundance of $H_2O/CO \approx 0.1$, or $H_2O/H_2 \approx 10^{-5}$, which is found for the galactic ISM, the optical depths of the two H_2O observed lines can be predicted as displayed in Figure 3. The 3σ upper limit to the 183 GHz line constraints then T_x to be lower than 20 K.

This result implies that the bulk of the H_2O molecules that we detect in absorption are not coming from hot dense cores, but are more widely spread and mixed with the

molecular cloud absorbing in CO. This is consistent with the high covering factor observed, and with the fact that the absorption technique selects preferentially cold gas (e.g. Combes & Wiklind 1996; Wiklind & Combes 1997). Also, the absorbing gas is situated in an intervening cloud which happens to be on the line of sight of the remote quasar. It is thus not necessarily an actively star forming region, as is the case for emission line observations of distant galaxies. It should be emphasized, however, that this result is based on the assumption of H_2O galactic abundance, which is poorly known; another solution could be a lower H_2O abundance, which will release the constraint of low temperature. However, even with an abundance of $H_2O/H_2 = 10^{-6}$ (or H_2O/CO=0.01), the excitation temperature should be lower than 30K (see fig 3). A higher H_2O abundance is not likely, unless we release the hypothesis of a constant T_x over the rotational ladder.

The present H_2O line detection at 331 GHz could not have been done without the enthusiastic support from the IRAM staff at the Pico Veleta. Bibliographic and photometric data have been retrieved from the NED data base.

Table 1. Observational parameters.

J_{KaKc}	3_{13}-2_{20}	1_{10}-1_{01}
ν_{lab} GHz	183.310	556.936
ν_{obs} GHz	108.811	330.592
Forward eff.[a]	0.92	0.77
Beam eff.[a]	0.74	0.19
T_A^*	$< 2.5\,\mathrm{mK}$[b]	$5.5\,\mathrm{mK}$
FWHM (km/s)	15.	15.
σ (9km/s)	$1.1\,\mathrm{mK}$	$1.3\,\mathrm{mK}$

[a]Main–beam efficiency $\eta_{\mathrm{mb}} = B_{\mathrm{eff}}/F_{\mathrm{eff}}$

[b*] 3σ upper limit in 15km/s channels

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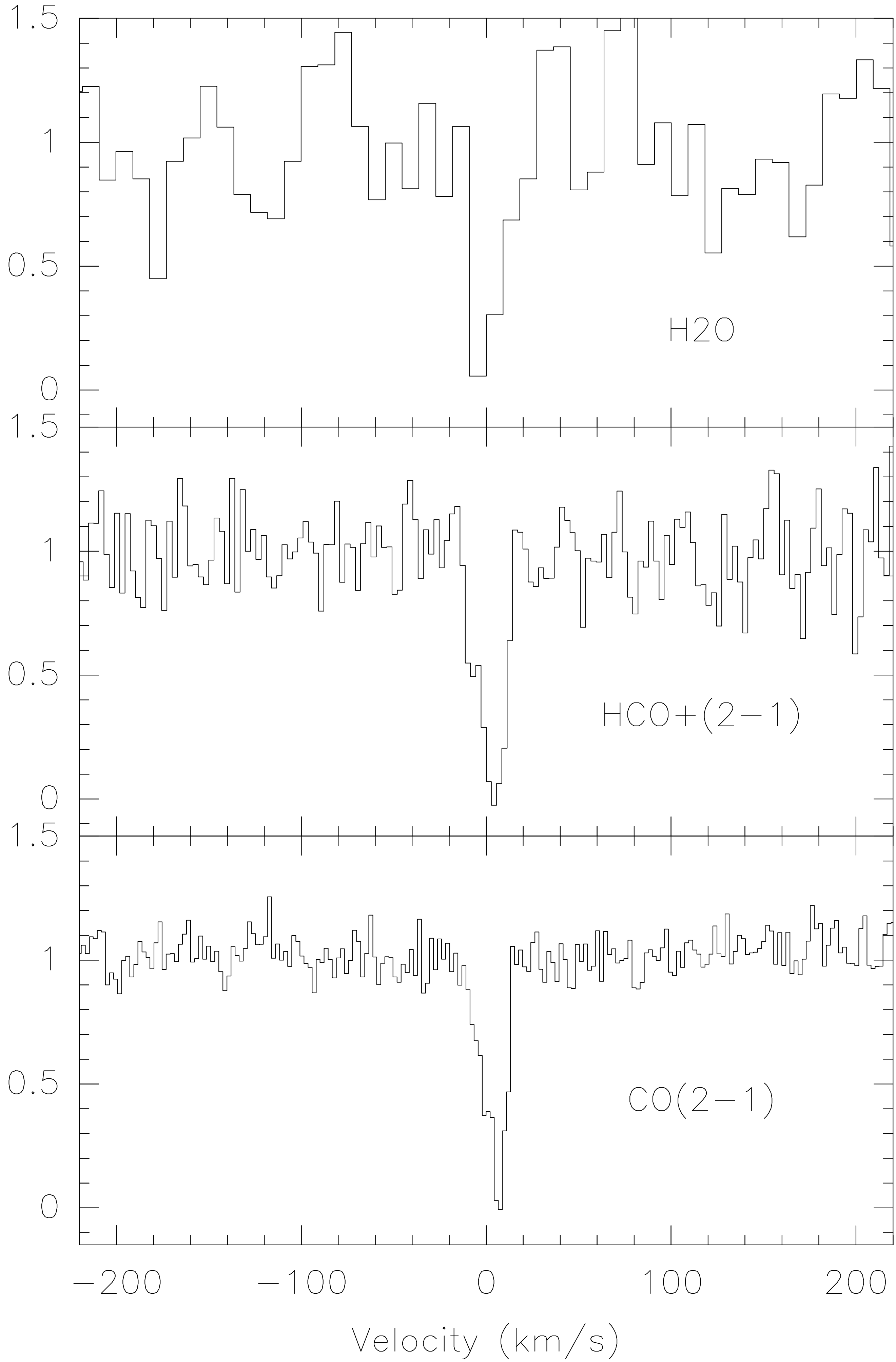
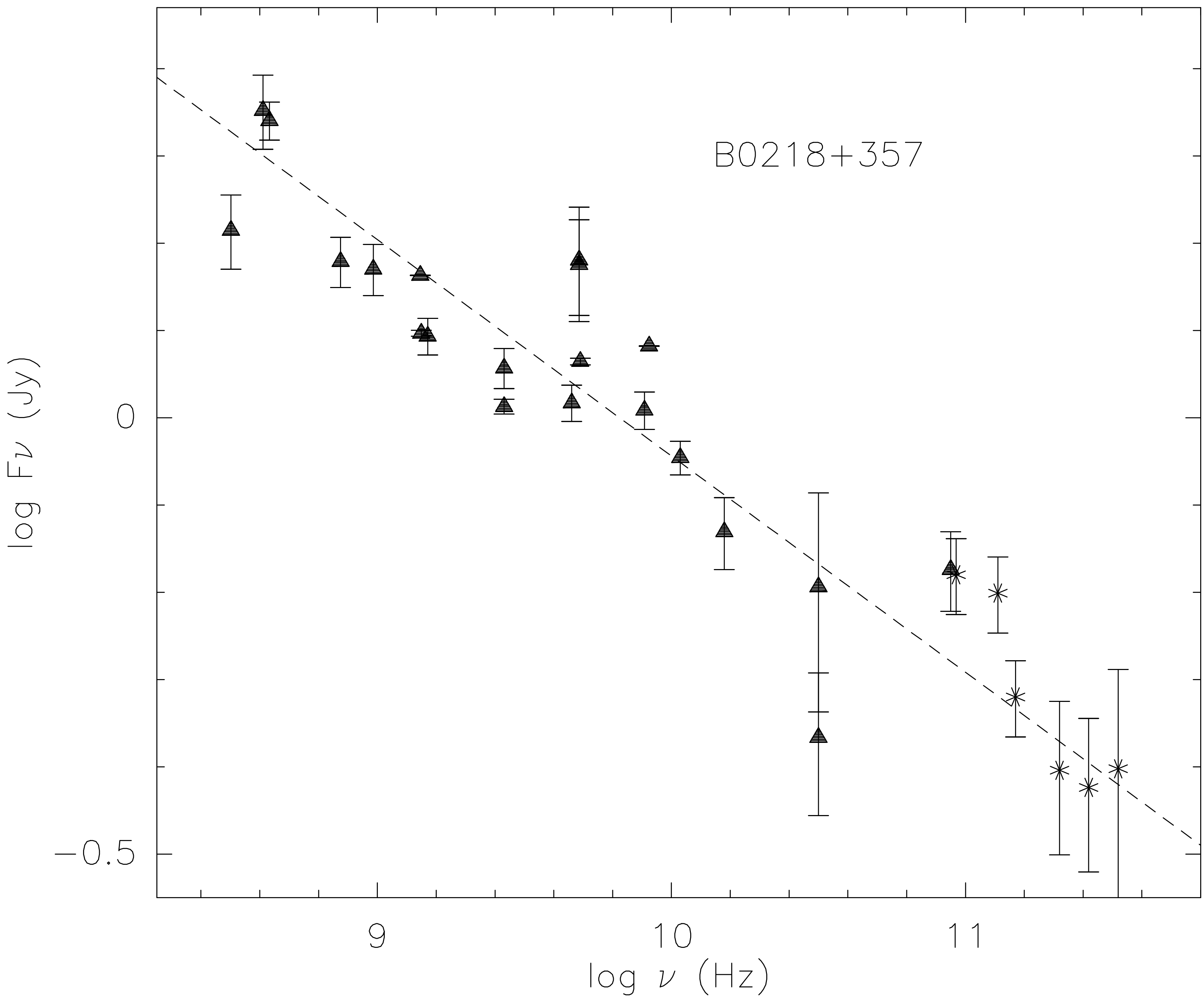
Fig. 1.— Spectrum of ortho–water in its fundamental line at 557 GHz, redshifted at 331 GHz, in absorption towards B0218+357 at z=0.68466. The line has the same width as the previously detected HCO^+(2–1) and CO(2–1) lines. The velocity resolution is 9.1, 2.8 and 2.2 km/s from top to bottom. Spectra have been normalised to the continuum level completely absorbed (33% of the total), i.e. 6, 37 and 27mK in T_A^* scale respectively.

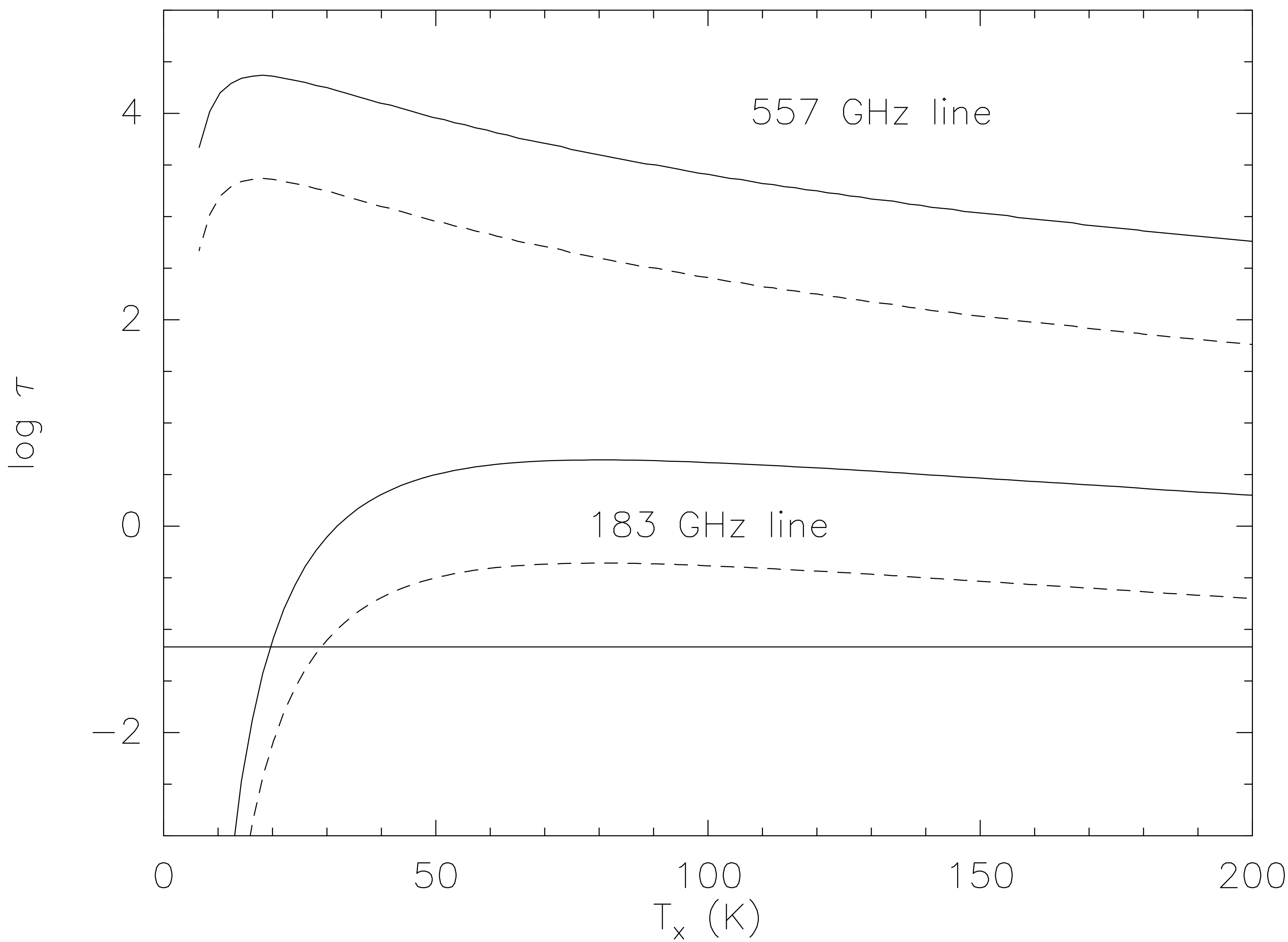
Fig. 2.— Radio continuum spectrum of B0218+357. Measurements from the literature (see NED for a compilation) are plotted with filled triangles, and the stars correspond to the present work. The dashed line is not a fit, but represents a power law of slope -0.25.

Fig. 3.— Logarithm of the central optical depth predicted for the two observed H_2O lines, for an assumed abundance $H_2O/H_2=10^{-5}$ (full line), and 10^{-6} (dashed line), as a function of excitation temperature. The horizontal line is the 3σ upper limit for the 183 GHz line, indicating that the excitation temperature is less than 20 K (or 30 K, dashed line).



1.5
1
0.5
0
H2O
1.5
1
0.5
0
HCO+(2−1)
1.5
1
0.5
0
CO(2−1)
−200
−100
0
100
200
Velocity (km/s)


B0218+357
log Fν (Jy)
0
−0.5
9
10
11
log ν (Hz)


557 GHz line
183 GHz line
log τ
Tx (K)
0
50
100
150
200
4
2
0
−2